

Optical Pulse Control of Electron and Nuclear Spins in Quantum Dots

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Introduction: Quantum information has the potential to revolutionize secure communications and computation, both important to the Department of Defense. The unique properties of quantum bits (qubits, units of quantum information) and the phenomenon of entanglement (non-local, non-classical correlation) prevent eavesdropping over quantum communication channels and enable the solving of problems that grow exponentially difficult with classical computation, including decryption of codes with long encryption keys.

Electron spins in quantum dots (QDs) are being widely investigated as qubits for storage and processing of quantum information, with the two different directions of the spin, up or down, forming the two states of the qubit. NRL is a leader in developing semiconductor QDs for quantum information, both in materials development and in probing the quantum nature of these nanometer-scale structures. Controlling the spin in these QDs, including increasing the spin coherence time, is a key area of NRL research. The electron spin coherence time in a QD, or lifetime of the qubit, can be at least microseconds, but the coherence is easily

masked by the many ($10^4 - 10^5$) randomly oriented nuclear spins that also exist in the QD (see Fig. 7(a)). The net nuclear spin acts as a temporally fluctuating magnetic field that randomizes the phase of the electron spin qubit. We use a train of picosecond laser pulses at wavelengths near an electronic QD transition to manipulate the electron spin polarization and thereby control the nuclear spin polarization. This technique can be used to extend the electron spin coherence time in QDs, making this system more attractive for quantum information applications.

Optical Spin Control: The primary effect of the laser pulses is to partially orient electron spins along the optical axis (z-direction in Fig. 7(a)). The spins then precess about a field composed of a perpendicular applied magnetic field of 3 T and the net nuclear spin field. This precession is observed for an ensemble of QDs at ~ 4 K (Fig. 7(b)) using time-resolved Faraday ellipticity (TRFE), which measures the electron spin projection along the optical axis as a function of time. The oscillations decay within a few hundred picoseconds due to inhomogeneity in the spin precession frequencies. The signal at negative delays is due to spins that precess with a frequency synchronized to a multiple of the laser pulse repetition rate (~ 81 MHz). Synchronized spins are efficiently polarized due to constructive interference over many pulses, while non-synchronized spins are not efficiently polarized. This phenomenon is known as spin mode-locking, and the associated nuclear dynamics have been previ-

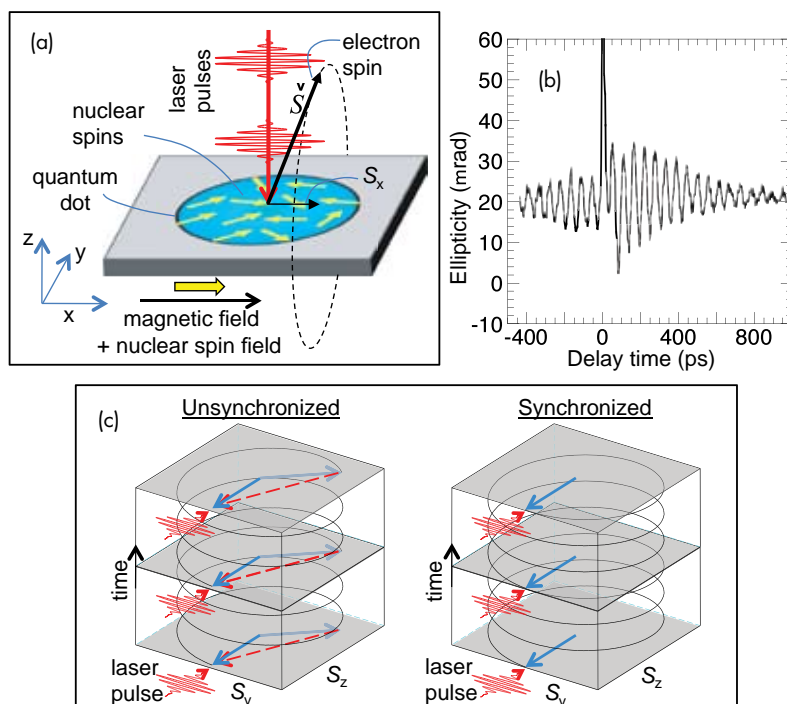


FIGURE 7

(a) Illustration of a quantum dot illuminated by a pulse train, showing nuclear spins (yellow) and the precessing electron spin. (b) Time-resolved Faraday ellipticity signal for an ensemble of QDs. (c) Illustration of electron spin precession for synchronized and unsynchronized spins. The unsynchronized spin polarization is ~ 2.5 times smaller than shown here. Red dashed arrows indicate the jump in the unsynchronized spin polarization from before a laser pulse (faint blue arrows) to after a laser pulse (blue arrows).

ously explored for laser wavelengths resonant with the QD transition.^{1,2} With the laser detuned from the QD transition, we find that a significant non-precessing spin component S_x is generated along the magnetic field axis, with the direction determined by the sign of detuning.

The nuclear spin dynamics depend on electron spin synchronization to the pulse train and the value of S_x . For an unsynchronized electron spin, the spin vector will suddenly jump each time a pulse hits (see Fig. 7(c)). These sudden jumps are likely to induce nuclear spin flips due to the hyperfine interaction. The direction of the nuclear spin flips is random for $S_x = 0$, but is directional for nonzero S_x . The nuclear spin flips change the electron spin precession frequency and can either push electron spins toward synchronization or away from it. The amplitude of the TRFE is a measure of how well the nuclear spins synchronize electron spins to the pulse train. Figure 8(a) displays the TRFE amplitude vs. QD detuning from the laser (δ_{QD}) for a series of pump intensities. At low intensities, for which the nuclear effects should be small, the amplitude is nearly symmetric about zero detuning, and it decays with detuning due to decreased coupling to the laser. At higher intensities there is a shift toward negative detunings due to increased spin synchronization for negatively detuned QDs. Theoretical calculations confirm this behavior (Fig. 8(b)), indicating that electron spins are pushed toward synchronization for

negatively detuned QDs and away from synchronization for positively detuned QDs. The difference is due to the changing sign of S_x . This result is further illustrated in Fig. 8(c), which displays the calculated probability distribution of the nuclear polarization for positive, negative, and zero detuning.

Conclusions: We have demonstrated that the direction of nuclear spin flips can be controlled with the detuning of an optical pulse train. This allows us to control the nuclear polarization and fix it at a precise value determined by the repetition rate of the laser. A fixed nuclear polarization will increase the coherence time of electron spin qubits and allow better control of the spin precession frequency. Precise nuclear control also suggests using nuclear spins, which have very long spin coherence times, to store quantum information.

[Sponsored by ONR]

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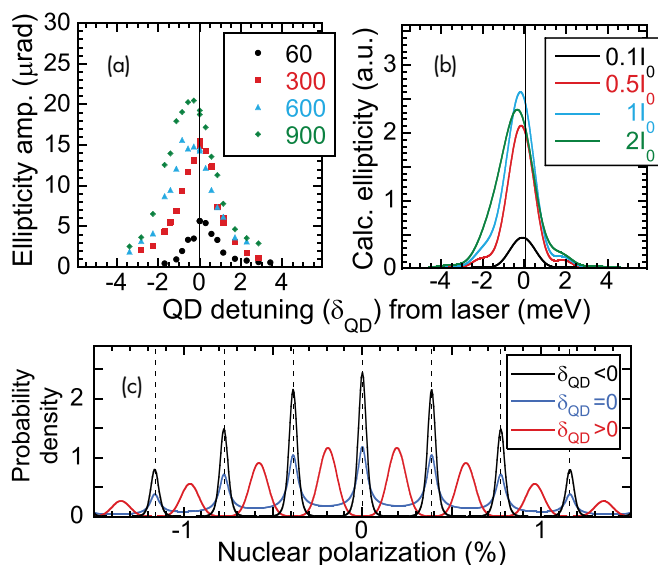


FIGURE 8

(a) Oscillation amplitude of TRFE vs QD detuning for a series of pulse intensities (in W/cm^2). (b) Calculated ellipticity vs QD detuning for a series of pulse intensities. (c) Calculated probability distribution of the nuclear polarization for three QD detunings: -0.8 , 0 , and $+0.8$ meV. Vertical dashed lines mark the nuclear polarizations that synchronize spin precession.